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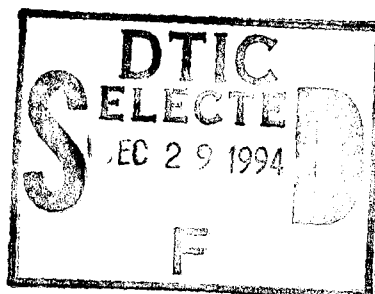


A Nuclear Electromagnetic Pulse (EMP) Vulnerability/Lethality (V/L) Taxonomy With Focus on Component Assessment

Brian G. Ruth

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1. INTRODUCTION

Among the effects generated by a nuclear burst, apart from blast, thermal, and nuclear radiation, is an electrical disturbance known as an electromagnetic pulse (EMP). This intense signal can achieve peak field strengths of tens of kilovolts per meter within several nanoseconds. The fields associated with an EMP can then couple into systems through electrical cables, antennas, and seams and apertures in metal screening enclosures, inducing large voltage and current transients on electronic input/output (I/O) ports. This phenomenon is known as *electrical overstress*, and can result in two types of effects: (1) upset, which is the generation of an undesired signal that temporarily corrupts circuit function, and (2) burnout (failure), which is the degradation of components via thermal or electrical breakdown and flashover to a state from which functional recovery is impossible.

An EMP assessment is usually done as part of an overall survivability/vulnerability/lethality analysis of a military system in a battlefield environment. This EMP-specific analysis involves several steps. First, the free-field electric and magnetic field components of the EMP are either calculated (based on a predetermined nuclear environment) or assumed from a given set of criteria. Then, a calculation is carried out to determine the amount of EMP coupling into a specific system. Finally, a screening procedure is carried out to determine which electronic components in the system are susceptible to EMP. Some thought is also usually given to determining whether component upset or burnout results from the electrical overstress, and the subsequent impact on mission completion is predicted.

In the past, a large effort was devoted to the assessment of components exposed to EMP. In the mid-1960's, Wunsch and Bell postulated a thermal breakdown model to predict thermal burnout in semiconductor p-n junctions (Wunsch and Bell 1968). Subsequently, analytical and computer models, based on the work of Wunsch and Bell, were investigated (Kleiner et al. 1974; O'Donnell and Tasca 1978; Yee, Orvis, and Martin 1983) and upset/burnout experiments were performed (Tasca, Peden, and Miletta 1972; Kalab 1981; Thomas and Diloreto 1985; Wenaas and Fromme 1985) in an attempt to formulate a methodology for component assessment. Most of this work was either system-specific or nonsystem-related, and thus difficult to apply to overall families of military systems. What is lacking to date is a unified EMP assessment methodology that can be applied to all military systems (or at least large classes of systems).

2. VULNERABILITY/LETHALITY TAXONOMY

The solution to the EMP assessment methodology problem lies in the implementation of the vulnerability/lethality (V/L) taxonomy to the analysis process. The V/L taxonomy is a mathematical framework developed by the Ballistic Vulnerability Lethality Division (BVLD)* of the Survivability/Lethality Analysis Directorate (SLAD), Army Research Laboratory (ARL), which clearly defines the elements of the V/L analysis process (Klopcic, Starks, and Walbert 1992). Within this framework, two critical concepts are defined:

- *V/L Space or Level.* A V/L space or level is defined as a set of points, where each point is a vector whose elements each define the status of a particular aspect of the system under analysis (SUA) or subsystem under analysis (SSUA). The number of points in a particular level is a function of the analytical granularity imposed on the SUA. There are four separate levels in the taxonomy: (1) Level 1, the set of all possible vectors defining initial conditions, consisting of the vector elements *threat definition* and *target definition* for each point in the space; (2) Level 2, the set of all possible vectors defining damaged component states; (3) Level 3, the set of all possible vectors defining a new system (a degradation of the original SUA); and (4) Level 4, which is the set of all possible vectors defining the overall post-threat battlefield utility of the SUA.
- *Mapping.* A mapping is a function that operates on a point (state vector) in one level to generate a time-evolved image point in the next level. The mapping function itself is an algorithm (or set of algorithms) that incorporates the physics or engineering of a real-time and real-space process (such as EMP coupling into a cable or chemical agent penetration into an enclosure). The mapping operator O_{n_1, n_2} is defined as the noninvertible function that maps a point in Level n_1 to an image point or locus of points in Level n_2 .

Figure 1 illustrates the generic V/L taxonomy. Note that the mapping operation $O_{3,4}$ is somewhat different from the previous mappings, as indicated by the thicker arrow. The $O_{3,4}$ mapping, which uses an algorithm based on operations research methodology, connects aggregates of coupled points within Levels 3 and 4 rather than individual points. Although the complete taxonomy as developed so far shows mappings from Level 1 to Level 4, it may require modification upon application to threat scenarios other

* The BVLD was formerly known as the Vulnerability/Lethality Division (VLD) of the Ballistic Research Laboratory (BRL).

than ballistic (as in a chemical threat scenario, where a Level 0 and an $O_{0,1}$ mapping are required to generate the threat definition in Level 1).

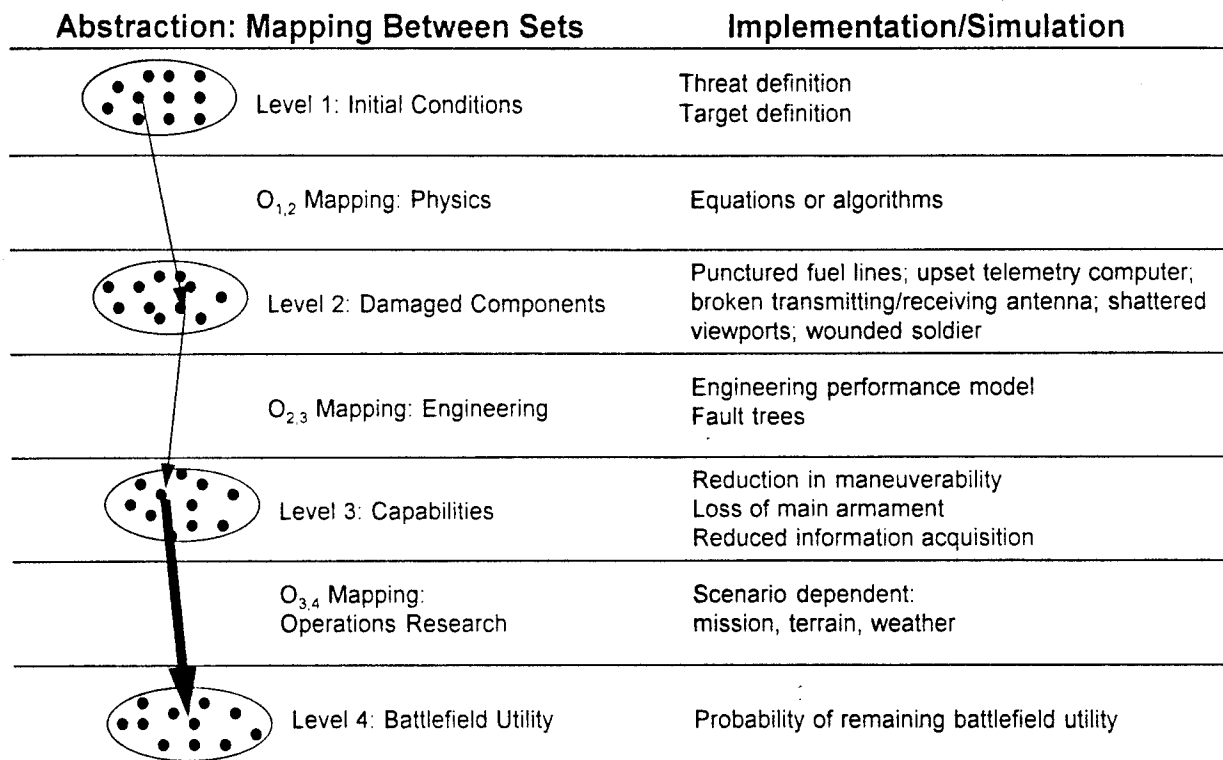


Figure 1. The vulnerability/lethality (V/L) taxonomy.

3. NUCLEAR EMP V/L TAXONOMY

The generic V/L taxonomy is now applied to the previously mentioned EMP assessment problem to generate a nuclear-EMP-specific V/L taxonomy (Figure 2). Level 1 defines the initial conditions, including the threat definition and the target definition. This information (a set of state vectors) is then operated upon by the $O_{1,2}$ (physics) mapping algorithm, which is a combination of three types of subalgorithms: (1) computer codes, which incorporate theoretical models of several physical processes; (2) databases, which provide empirical information on physical processes, and may incorporate results of computer code calculations, experiments, and "engineering judgments"; and (3) experiments, which actually reproduce in real time/real space part or all the mapping operation. Finally, Level 2 is reached, where the state vectors describing the SUA in Level 1 have time-evolved to a point where component damage (upset and burnout) information is included in the vector elements. At this time, the nuclear EMP V/L taxonomy terminates at Level 2, since an $O_{2,3}$ engineering mapping operator has yet to be developed.

4. LEVEL 1 AND $O_{1,2}^1$ SUBMAPPING

Now the specific vector sets and subalgorithms that make up the nuclear EMP V/L taxonomy are addressed. At this point, it is convenient to define two submappings within the $O_{1,2}$ mapping; the operators associated with these submappings are designated $O_{1,2}^1$ and $O_{1,2}^2$, and pertain to the algorithms concerning EMP free-field coupling and electrical overstress on components, respectively (see Figure 2). Since the focus of this report is on the submethodology of component assessment, the $O_{1,2}^2$ submapping and the resulting paths into Level 2 are of principal interest and are thus addressed in detail. However, to make plain the operation of the taxonomy as a whole, Level 1 and the $O_{1,2}^1$ submapping are first briefly discussed.

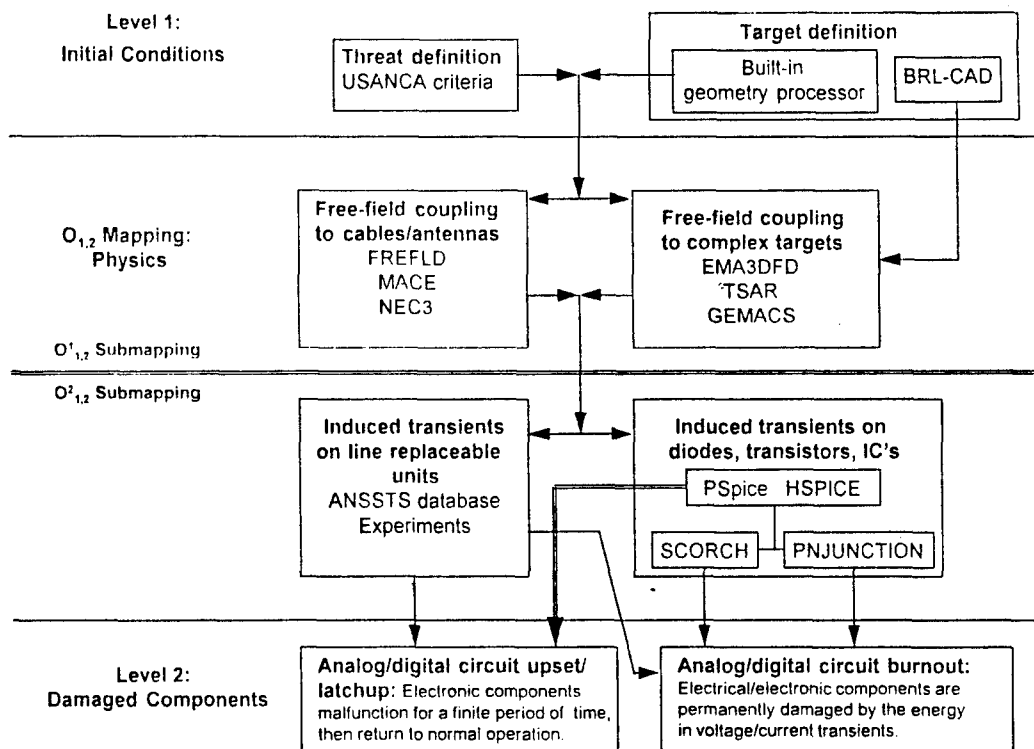


Figure 2. The nuclear EMP V/L taxonomy.

4.1 Level 1: Initial Conditions. As previously noted, Level 1 of the nuclear EMP V/L taxonomy is made up of two descriptive sets of vector elements, namely the threat definition and the target definition. The threat definition is a physical description of the free-field EMP waveform, which includes specified amplitude, rise time, pulse width, decay time, polarity, and spectral content. The threat definition itself is based on criteria established by the U.S Army Nuclear and Chemical Agency (USANCA) for Army systems. The target definition is either a numerical or three-dimensional solid geometric

(BRL-CAD) model of the SUA. The information in the threat definition and target definition elements is combined and "fed" into the $O_{1,2}^1$ algorithm.

4.2 $O_{1,2}^1$ Submapping. Two separate analysis modules are included within the $O_{1,2}^1$ submapping: the "free-field coupling to cables/antennas" and the "free-field coupling to complex targets" modules. The former module, containing three computer codes, is used to calculate coupling between the free-field EMP waveform and long cable and RF antenna inputs (if any) into the SUA or SSUA ("front-door" coupling). The latter module, also containing three computer codes, addresses more complex coupling between the free-field EMP waveform and subtle entry pathways into the SUA/SSUA, such as asymmetric apertures and EM-leaky seams in conducting structural walls and surfaces ("back-door" coupling). The codes in the complex targets module are in general more sophisticated than those in the cables/antennas module, with FREFLD being the least algorithmically complex (transmission-line solution) and GEMACS the most algorithmically complex code (a combination of method-of-moments, geometrical theory of diffraction, and finite-difference time-domain formalisms; modeling EMP-cable/antenna coupling is a subset of GEMACS' overall capability). If increasing algorithmic complexity directly results in higher resolution analytical granularity imposed upon the SUA/SSUA, then it can be argued that GEMACS is the preferred code to use when a detailed EMP coupling analysis is required. (Within the context of the V/L taxonomy, the modeling validity of the listed codes is given; however, all codes will require some experimental validation before they can be implemented as part of a real system analysis.)

Level 1 and the $O_{1,2}^1$ submapping within the nuclear EMP V/L taxonomy will be addressed in greater detail in a future report (Mar, to be published).

5. $O_{1,2}^2$ SUBMAPPING

The results of the $O_{1,2}^1$ submapping are now fed into the $O_{1,2}^2$ submapping algorithm. At this point in the analysis process, the calculated threat data are the Thevenin-equivalent open-circuit voltage and short-circuit current corresponding to an EMP-induced transient on either a cable or an electronics I/O port.* Next, a decision is required involving the analytical granularity imposed upon the SUA/SSUA: what is

* Within the context of this report, it is assumed that the $O_{1,2}^2$ submapping commences after the transient signal has passed through any terminal protection devices (TPDs) which might be installed in the system/subsystem. TPDs are devices which either re-route or suppress transient signals as they penetrate a system/subsystem; these protection devices are usually placed on the terminals of cables which penetrate a facility, enclosure, or piece of equipment.

the spatial "resolution" of the component that intercepts the transient signal? The resolution can range from a single passive component (resistor, capacitor, inductor) or semiconductor device to the entire SUA. As an aid in making this decision, a demarcation is established in the component resolution spectrum, resulting in two distinct analysis modules, namely the "induced transients on line replaceable units (LRUs)" and the "induced transients on diodes, transistors, and IC's (integrated circuits)" modules (see Figure 2). Now, one can decide which mapping vector to follow by determining the extent of the available circuit documentation describing the SUA/SSUA. This decision may still be difficult to make if only limited circuit documentation is available and could require at some point tracking back and forth between modules.

5.1 Induced Transients on LRUs.

5.1.1 ANSSTS Database. If the decision is made to pursue the analysis of components at the resolution of the line-replaceable unit (LRU) or larger scale, then the left-hand path in Figure 2 is chosen. Figure 3 illustrates the LRU analysis module in greater resolution. The principal tool in this module is the Army Materiel Command (AMC) Nuclear Survivability Status Tracking System (ANSSTS), which is a database of combined experimental and analytical nuclear-threat survivability data developed on over 500 LRUs, which in turn are elements of 11 fielded Army systems (Lambert 1993). The data in ANSSTS address survivability criteria levels for all the nuclear threats (blast, thermal, initial nuclear radiation (INR), and EMP) in terms of a "met/not met" criterion. ANSSTS is written in the RBASE® database language; accepted input parameters are LRU or system/subsystem number; output is in the form of a printed report describing the maximum survivability levels that an individual LRU or system/subsystem was subjected to through either experimentation or analysis. ANSSTS also gives the user a limited capability to adjust the component resolution within a system by determining (1) whether a specific LRU is a subcomponent of another LRU, and (2) which LRUs contain a specific LRU as a subcomponent.

5.1.2 Experiments. Unfortunately, in its present state, ANSSTS contains no data on LRU or system/subsystem *vulnerability* levels (current work will, however, soon produce an improved version of ANSSTS, converted into the FoxPro® database language, with some limited vulnerability data). This deficiency may be rectified by experiments conducted on those components where missing data are required to complete an EMP assessment. Two principal modes of experimentation are useful (Dittmer et al. 1986):

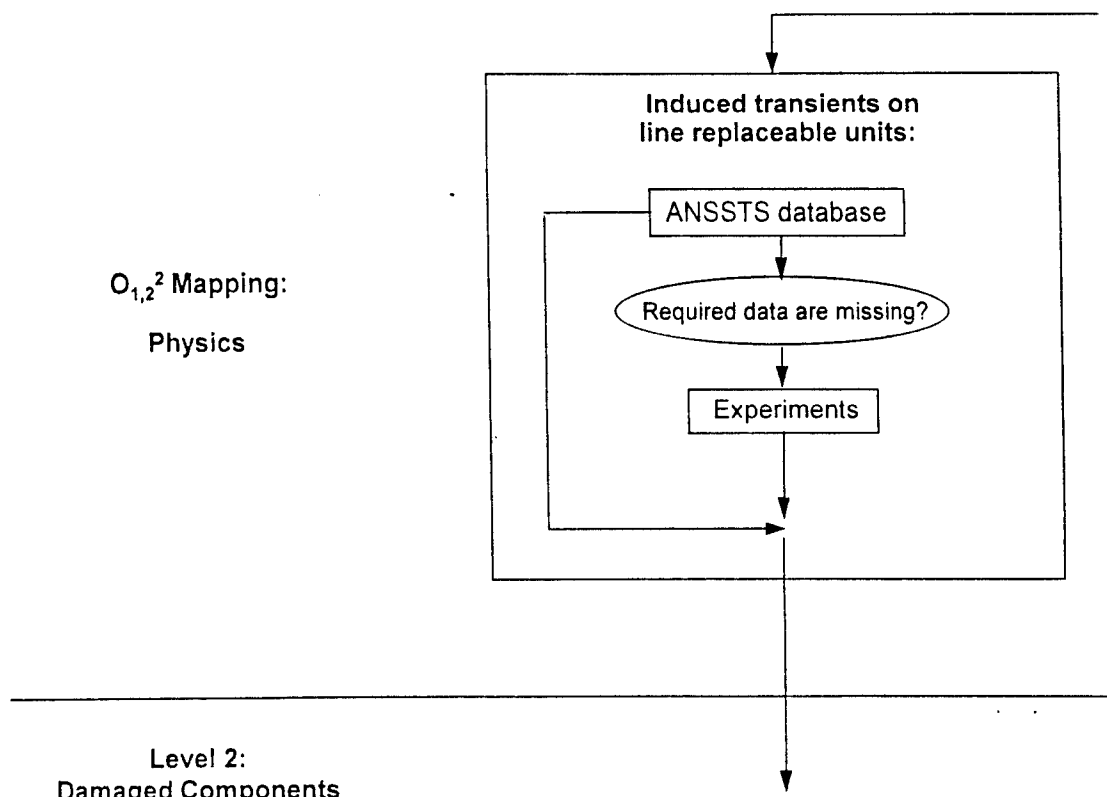


Figure 3. The “induced transients on LRU's” module within the $O_{1,2}^2$ submapping.

- *Full-scale EMP field illumination.* This technique allows for entire system/subsystem exposure to a simulated EMP (which is approximately an EM plane wave). High-power drivers allow for the generation of threat-level EMP signals. Waveforms of either vertical and horizontal polarization may be produced; with knowledge of the system/subsystem coupling function for each polarization, one can determine the coupling for any arbitrary polarization. There are two types of full-scale illumination simulators: (1) the bounded-wave simulator, which contains a finite conducting-wall volume wherein the system/subsystem is exposed to an EMP; and (2) the antenna simulator, which is either a large monopole (above a ground plane) or dipole antenna that produces a pulse in a vertical or horizontal polarization, respectively.

- *Current injection experiments.* This technique is used to determine (1) the transfer coupling functions from cables to circuit-board electronics via equipment terminals, and (2) upset or burnout thresholds of electronic components of a resolution ranging from box-level to individual semiconductor device. The pulsed current signal can be injected either directly or inductively onto the cables of interest.

Either of these two types of experiments can be used to determine the occurrence of upset and/or burnout due to electrical overstress; however, the current-injection experiment is the more direct approach and therefore yields the more dependable data.*

5.2 Induced Transients on Diodes, Transistors, and Integrated Circuits. If there is sufficient available circuit documentation on the SUA/SSUA, then the right-hand path in the O_{12}^2 submapping (see Figure 2) is preferred, which is the "induced transients on diodes, transistors, and IC's" analysis module (Figure 4). However, as was previously mentioned, it may be difficult to determine the minimum level of documentation required for a meaningful analysis. Since most operating Army systems contain elements of command, control, and communication (C3) electronics of a very sophisticated and complex nature, the principal analysis concern in an EMP assessment should be the interface circuitry that connects an I/O port to the "brains" of the SUA/SSUA. This interface circuitry is composed of passive devices, discrete semiconductor devices, and possibly several ICs, and is usually designed to protect the C3-processing electronics from undesired high-level noise and electrical overstress (these protection devices are usually a combination of filters, which suppress and/or attenuate specific-frequency signals and limiters, which limit current transmitted through to the protected device). Thus, if the system documentation extends down to the interface circuitry level, it is probably complete enough for a first-cut analysis. A re-evaluation of the available circuit documentation would then have to be made if a detailed circuit analysis of the electronics beyond the interface circuitry is required.

5.2.1 EMP Susceptibility Screening. The first step in the diodes/transistors/IC's analysis module involves an EMP susceptibility screening on the SUA/SSUA. The V/L taxonomy resolution is again increased to produce the EMP susceptibility screening flowchart shown in Figure 5. This screening automatically precludes nonmission-essential (Saccetti and Schumacher 1984)** and intrinsically hard (nonelectronic) subsystems from further analysis. Then, the resolution of the component under analysis

* There is a third mode of EMP experimentation which utilizes a **continuous wave (CW)** source, such as ARL's Continuous Wave Instrumentation System (CWIS). This method involves driving an antenna with a CW signal generator, swept either continuously across a wide band of frequencies or discretely at several frequencies across the EMP spectrum. However, CW experimentation is useful only in characterizing linear system parameters, such as coupling and shielding effectiveness; for true upset/latchup/burnout characterization, a nonlinear transient pulse is required.

** The classification *mission-essential* defines a set of conditions, of which the classification *mission-critical* is a subset. If damaged, mission-essential components would require replacement either to prevent damage to other (possible more vulnerable) components or to maintain system readiness in the long term (Saccetti and Schumacher 1984). The failure of mission-critical components would jeopardize the successful completion of the mission. Within the context of this report, mission-essential components are principally filters and limiter circuits.

(CUA) is established, and subsequent analysis paths determined. Piece-part electronic components are routed directly to the SCORCH database for vulnerability assessment, while larger components are directed to the SPICE circuit analysis codes, with special attention to be paid to identified and/or suspected vulnerable circuit elements.

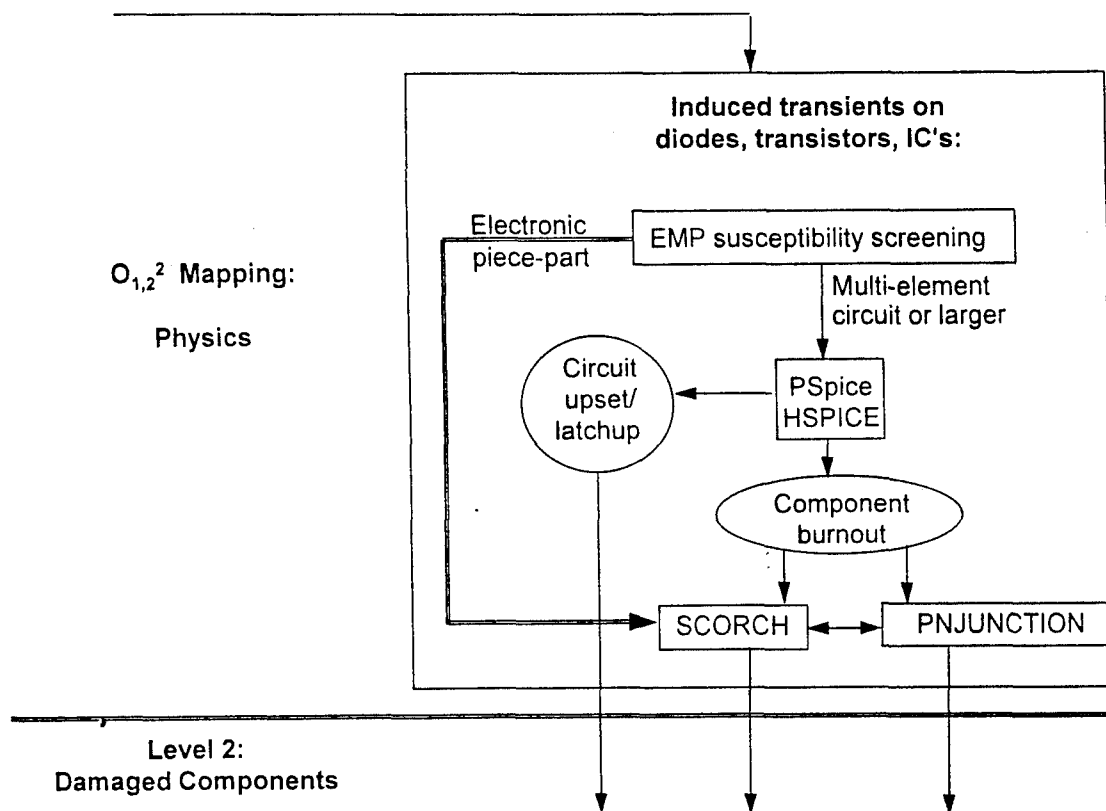


Figure 4. The "induced transients on diodes, transistors, and integrated circuits" module within the O_{1,2}² submapping.

The circuit element models in SPICE2 (henceforth to be referred to simply as SPICE) cover most of the common devices currently in use in commercial and military systems. These element models include (1) passive devices, such as resistors, capacitors, inductors, transformer cores, and transmission lines; (2) voltage and current sources (with voltage-controlled, current-controlled, and independent models for each type of source); (3) diodes; (4) bipolar transistors; (5) field-effect transistors (FETs), including the junction FET (JFET), gallium arsenide FET (GaAsFET), and the metal-oxide semiconductor FET (MOSFET); and (6) switches, which are bivalued resistors, with value-switching either voltage- or current-controlled. SPICE will calculate voltage or current levels on specified circuit elements in either the frequency or time domain.

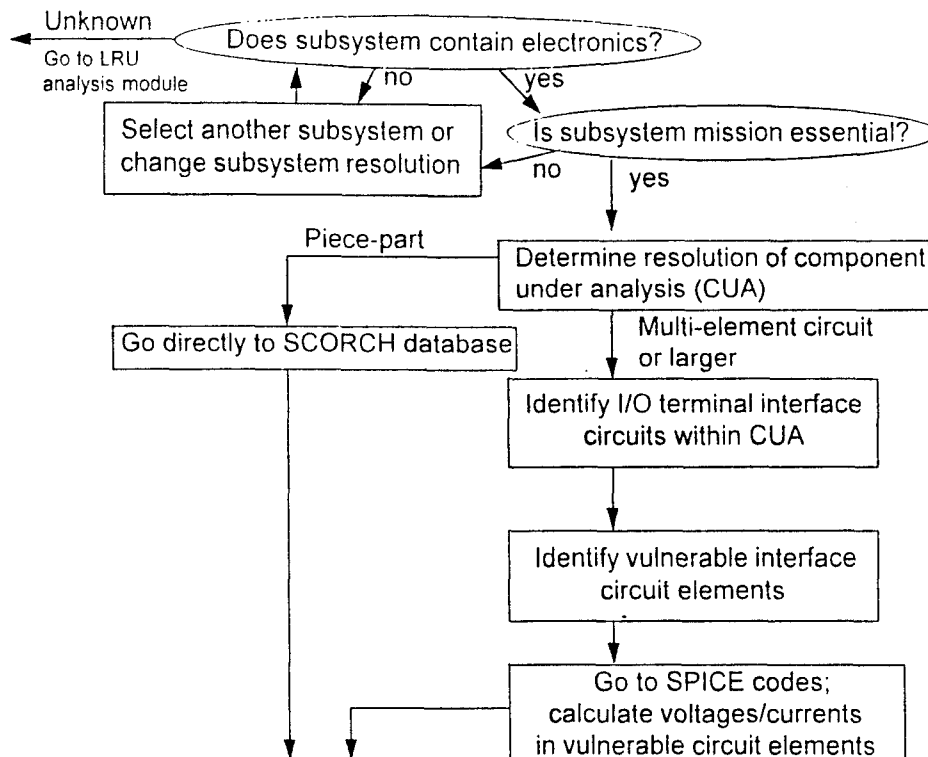


Figure 5. The EMP susceptibility screening submodule within the “induced transients on diodes, transistors, and integrated circuits” module.

SPICE is in the public domain, but since UC Berkeley provides no outside support or consulting services for users, commercial versions of SPICE have been developed, each version advertising extensive customer support. These commercial versions fall into three distinct groups (Tuinenga 1988; Meta-Software, Inc. 1992):

- *Mainframe/workstation versions.* The original commercial versions of SPICE were designed to run on mainframe computers, and have subsequently been developed to operate in a UNIX environment on workstations.
- *PC-based versions.* With the introduction of the personal computer (PC), several other commercial SPICE clones were developed. However, these PC-based versions are exact clones of SPICE, even down to errors in the parent code, and thus are of little interest.

- *Advanced versions.* These packages contain greatly rewritten or completely new modeling algorithms from those in SPICE, but still adhere to the UC Berkeley standards for circuit description. All advanced versions of SPICE include a special focus on analog circuit simulation.

Determining which version of SPICE is best to use will depend on the resolution and complexity of the CUA.

Two particular SPICE clones have been selected for inclusion in the nuclear EMP V/L taxonomy, based on their particular focus. For analysis of the interface circuitry identified in the EMP susceptibility screening, PSpice® is probably the best code to employ. PSpice is one of the advanced versions of SPICE, and focuses on simulating analog circuits, which are the most likely components of interface circuitry. If the interface circuitry fails to deter the transient signal from entering the electronic "brains" of the SUA/SSUA, then the HSPICE® code is employed. HSPICE, a mainframe/workstation version of SPICE, devotes special attention to vendor library IC models, which allows for detailed analysis of such components as analog-to-digital (A/D) and digital-to-analog (D/A) converters, analog multiplexers, and operational amplifiers. However, the usefulness of HSPICE will be limited by circuit complexity; for example, a digital signal processor (DSP), which is an integral component of C3 systems, is a microprocessor computer chip containing over 1 million transistors, and is obviously beyond the practical scope of any circuit simulation code. HSPICE analysis, when employed, should be limited to identifiable and manageable mission-critical subcircuits. Also, either code may be used to determine whether a transient signal induces upset and/or latchup in components, particularly in digital circuits.

5.2.2 SCORCH. For analysis of electronic piece-parts of a component resolution discrete device (up to and including the IC level), the Source for Component Overstress Response Characteristics (SCORCH) program is best to use. SCORCH is a computer database/analysis tool that provides vulnerability information on electronic components that are subjected to high-amplitude electrical transients. These transients may arise from natural-environment electrical overstresses (lightning, electrostatic discharge) as well as from an EMP. SCORCH evolved from SUPERSAP2 (System Analysis Program), which was developed by the Phillips Laboratory* in Albuquerque, NM, for susceptibility analysis of electronics exposed to an EMP. SUPERSAP2 was converted into SCORCH in the mid-1980's, and responsibility

* Formerly known as the U.S. Air Force Weapons Laboratory.

for maintaining the program was transitioned to the Mission Research Corporation (MRC) in Albuquerque, NM (Mission Research Corp. 1993).

SCORCH provides three different classes of vulnerability information to the analyst:

- *Empirical failure models.* Models are derived from experimental data for several different types of electronic components, including diodes, transistors, digital and analog ICs, resistors, and capacitors. The data are gathered from current-injection experiments on small samples (20 to 30 units) of each component, using either rectangular pulses, damped sinusoids, or triangular waveforms. In general, the failure models yield a required failure-level power as a function of pulse duration.
- *Electrical design parameters.* In this class, up to 40 electrical design parameters are included per database device entry; devices included are diodes, transistors, and analog and digital ICs. There are approximately 250,000 device entries, derived from the D.A.T.A. Digest® compendium of semiconductor piece-part design parameters. Included in this class are several prediction algorithms that estimate the failure thresholds of semiconductor devices (such as Wunsch-Bell damage constants) based on manufacturer-provided electrical characteristics.
- *Experimental data.* The third class is made up of experimental failure data on specific individual semiconductor devices. These piece-part failure data may be referenced by part type, topographical design, or fabrication technology.

SCORCH is written in the RBASE database language and uses a menu-driven executive program for data collection and extraction.

Within the O_{12}^2 mapping of the nuclear EMP V/L taxonomy, the SCORCH database is accessed either directly from the EMP susceptibility screening submodule (for electronic piece-parts, as previously mentioned) or through the SPICE circuit simulation codes. The latter pathway is chosen if electronic component failure levels within the SUA/SSUA need to be determined.

5.2.3 PNJUNCTION. If the discrete electronic device under vulnerability analysis is a bipolar semiconductor and the transient pulse duration $T_{pulse} \geq 100$ ns, then there is a computational alternative

to SCORCH called PNJUNCTION, which is a code that uses a one-dimensional drift-diffusion model to simulate electron-hole transport across a semiconductor p-n junction. PNJUNCTION, written in FORTRAN, was specifically designed for ARL by Victor van Lint (formerly of MRC, Albuquerque) in 1993 (Fazi, private communication). The model used in PNJUNCTION incorporates the following equations:

- *Poisson's equation.* Assuming a quasi-steady-state condition, the operating wavelength within the semiconductor is much larger than the device dimensions. Thus, Maxwell's equations can be reduced to Poisson's equation:

$$\nabla^2 \phi = \frac{q}{\epsilon} (n - p - N). \quad (1)$$

- *Current continuity equations.* If a homogeneous medium is assumed within the device cross section, then the current continuity equations for electrons (Eq. 2a) and holes (Eq. 2b) can also be determined from Maxwell's equations:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \vec{J}_n - \frac{1}{q} R(n, p), \quad (2a)$$

$$\frac{\partial p}{\partial t} = \frac{1}{q} \nabla \vec{J}_p - \frac{1}{q} R(n, p), \quad (2b)$$

where the electron and hole current densities are respectively defined by

$$\vec{J}_n = -q\mu_n n \nabla \phi + qD_n \nabla n, \quad (3a)$$

$$\vec{J}_p = -q\mu_p p \nabla \phi + qD_p \nabla p. \quad (3b)$$

In the previous equations, ϕ is the electrostatic potential; n and p are the densities of conduction band electrons and valence band holes, respectively; \vec{J}_n and \vec{J}_p are the electron and hole current densities; ϵ is the conduction medium dielectric constant; q is the electron charge; N is the net density of donors and acceptors; $R(n,p)$ is the recombination-generation function; μ_n and μ_p are electron and hole mobilities; and D_n and D_p are electron and hole diffusion coefficients. Also, conservation of total current is assumed ($\vec{J} = \vec{J}_n + \vec{J}_p$). In PNJUNCTION, the previous equations are numerically implemented through the Yee Finite Difference algorithm to solve for voltage and current profiles (Fazi, private communication).

As it presently exists, PNJUNCTION cannot calculate failure voltage and current levels across a p-n junction. The failure mechanism that results in these voltages and currents is called second breakdown; it arises when a transient signal induces a negative voltage drop across a p-n junction (reverse bias; see Figure 6). A negative saturation current is then induced, which results in an undesired negative voltage across the p-n junction (first breakdown). As the negative voltage grows, it reaches a point where conduction channels are burned across the p-n junction (second breakdown). This finally results in a decrease in the reverse bias, where the semiconductor device appears to have a negative resistance (decreasing voltage/increasing current). For PNJUNCTION to properly model the second breakdown phenomenon, the thermal diffusion equation

$$\frac{\partial^2 T}{\partial x^2} - \left(\frac{\tau C_H}{k} \right) \frac{\partial T}{\partial t} = 0 \quad (4)$$

must be implemented into the code, where T is the temperature, τ is the material density, C_H is the specific heat, and k is the thermal conductivity.

Within the nuclear EMP V/L taxonomy, PNJUNCTION can be chosen as an alternative to the SCORCH database when either (1) there is no entry within SCORCH on a specific bipolar semiconductor device of interest, or (2) the prediction models for bipolar devices used within SCORCH fail to provide the analytical granularity required for an accurate answer. However, the analytical granularity within PNJUNCTION itself limits its utility to only the smallest possible component resolution; practical use of the code should be limited to single bipolar semiconductor devices that are specifically mission-critical elements of an SUA/SSUA.

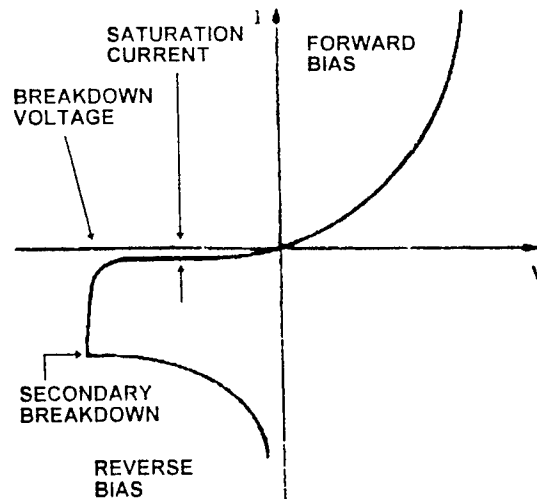


Figure 6. Secondary breakdown across a p-n junction within a bipolar semiconductor device.

6. LEVEL 2

Five different specific vector trajectories enter Level 2 via the $O_{1,2}^2$ mapping in the nuclear EMP V/L taxonomy (Figure 2). Vectors mapped from Level 1 to Level 2 along these paths may enter one of two damage states:

- *Digital circuit upset/latchup.* Electronic components will either (1) malfunction for a finite period of time, then gradually return to normal operational states (upset), or (2) lock into a voltage/current saturation state, from whence a return to a normal operating state is achieved only via a system/subsystem power reboot (latchup). If there are multiple transient signals intercepting the components, then the time required for a return from upset to normal operating states is a function of the delivery frequency of the transients. In general, upset/latchup may occur in both analog and digital circuits, but will have a more frequent mission-critical effect in the latter.
- *Analog/digital circuit burnout.* Both electrical (passive devices) and electronic (semiconductor devices) components are permanently damaged by either the thermal or electrical energy coupled into the electronics from the transient signal(s). The amount of energy required for burnout is a function of both component type and T_{pulse} , and ranges from the relatively low energy released during second breakdown in a bipolar semiconductor ($T_{pulse} \geq 100$ ns) to significantly higher energies released in an electrical arc across a thin-film resistor ($T_{pulse} < 100$ ns).

One can most easily formulate fault trees (within the $O_{2,3}$ mapping) based on the damage state vectors that completely describe the SUA by starting out in Level 1 with a hierarchical target description. Such a target description is organized in a pyramidal hierarchy, with the complete system at the top, which is then broken down into parallel subsystems, sub-subsystems, and so on (Figure 7). The BRL-CAD modeling package was specifically designed to create hierarchical target descriptions, and is thus the ideal choice both for implementing a target description in Level 1 and for guiding the formulation of fault trees within the $O_{2,3}$ mapping (Deitz and Applin 1992). However, the present component resolution within BRL-CAD focuses down to the LRU level; a methodology is required to determine a probability of damage (P_d) for an electronic component of resolution R_{comp} in the range $R_{piece-part} \leq R_{comp} \leq R_{LRU}$, where $P_d = P_d(R_{comp}, V_{pulse}, T_{pulse}, \rho_{x,y,z}, \epsilon_{x,y,z})$ and V_{pulse} = magnitude of transient threat signal, $\rho_{x,y,z}$, $\epsilon_{x,y,z}$ = physical and electrical location of component relative to system/subsystem, respectively. The P_d associated with an electronic component should be a combination of both a probability of upset (P_u) and a probability of failure (P_f).

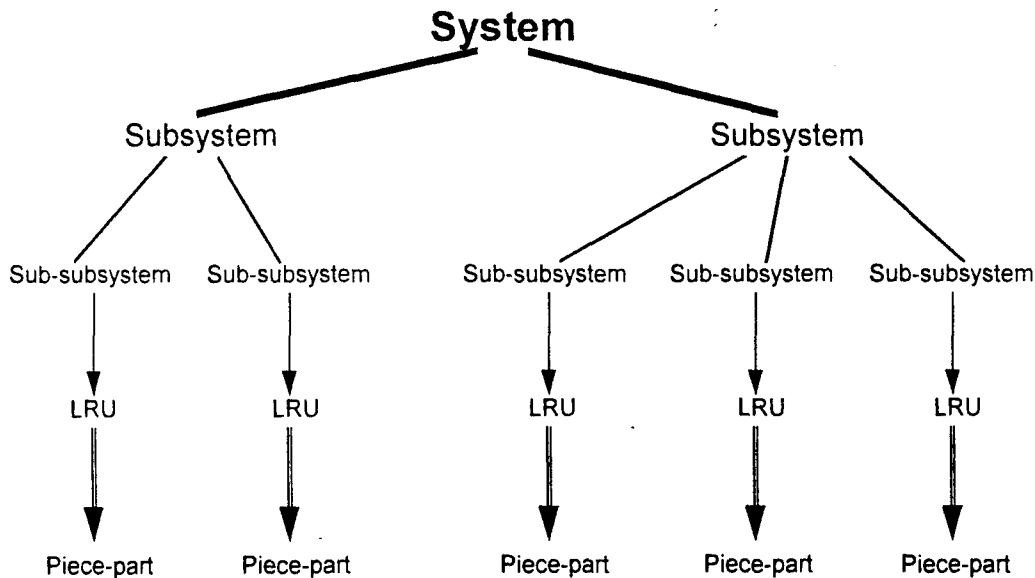


Figure 7. Organization of a hierarchical target description. Arrows indicate continua (possibly multi-branched) of possible component resolutions, from which discrete resolutions are chosen.

7. CONCLUSIONS AND RECOMMENDATIONS

A generic taxonomy that was previously developed (Klopčič, Starks, and Walbert 1992) for the V/L analysis process has been applied to the nuclear EMP assessment problem, in particular to the assessment of system/subsystem components exposed to EMP-induced transients. The taxonomy was used to generate a methodology that uses a combination of computer codes, databases, and "engineering judgments" to guide the analysis process from the coupling of a transient signal onto an I/O port of the CUA to the resulting temporary/permanent damage state. Although this methodology was designed for analysis of damage due to transients induced by a high-altitude EMP (HEMP) threat, it can also be applied to the analysis of components exposed to surface- and air-burst EMP, as well as system-generated EMP (SGEMP).*

Within the levels and mappings in the nuclear EMP V/L taxonomy discussed in this report, there are still some unclear areas that need to be addressed. For example, it remains somewhat uncertain how much system documentation is required to make an informed decision on the proper analysis module to select within the $O_{1,2}^2$ submapping. For that matter, how does one routinely select an appropriate component resolution when beginning the $O_{1,2}^2$ submapping? Another area of uncertainty is associated with the "humans-in-the-loop" class of military systems, in which the mission response of a system is a function of the human/system interface. An example of such a system might be a communications network of mobile transmitter/receiver units, the layout of which is the decision of the local military commander. In the past, these qualitative parameters were quantified by making the above-mentioned "engineering judgments."

The field of fuzzy set theory may provide a better methodology for the quantification of uncertainties within the nuclear EMP V/L taxonomy (Terano, Asai, and Sugeno 1992). As an example of the applicability of this theory, a simple hypothetical component database containing EMP vulnerability data on electronic diodes is "fuzzified" so that it covers diodes not in the database. This example is presented in the Appendix.

* If the HEMP threat is replaced by an SGEMP threat, the threat definition in Level 1 and the $O_{1,2}^1$ submapping within the nuclear EMP V/L taxonomy will require modification.

Finally, there is the developmental problem of extending the existing nuclear EMP V/L taxonomy from the damaged components state of Level 2 down to the system capabilities state of Level 3. Working within the hierarchical structure of BRL-CAD, $O_{2,3}$ mapping fault trees at the electronic piece-part resolution level (when required) must be developed to determine how EMP-induced component damage affects system capabilities. Addressing the inherent uncertainty in the $O_{2,3}$ mapping requires a judicious combination of stochastic simulation and fuzzy Bayes decision-making theory (the subject of a future paper). This approach will allow for the introduction of combined battlefield threat effects (nuclear, chemical, biological, electromagnetic, ballistic) into the nuclear EMP V/L taxonomy, which in turn might require either a new suite of combined effects taxonomies or an intertaxonomy mapping function.

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APPENDIX:
A FUZZY DATABASE OF COMPONENTS SUBJECTED TO ELECTRICAL OVERSTRESS

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Table A-1 displays a hypothetical database containing operating parameters for five different diodes, including p-n junction cross-sectional area A_{p-n} , asymptotic forward bias voltage V_{p-n} , saturation current I_{sat} , and first breakdown voltage V_{FB} . Taken together, these four parameters fairly well characterize the current/voltage relationship in a diode (see Figure 6 in the body of the report). There is a fifth data entry for each of the diodes, the failure burnout current I_{fail} , which, when multiplied by V_{FB} , yields the diode failure power. This failure current is a function of the four design parameters listed above, i.e., $I_{fail} = I_{fail}(A_{p-n}, V_{p-n}, I_{sat}, V_{FB})$. Within the context of the hypothetical database, assume that I_{fail} was determined by failure experiments on lots of 30 "identical" samples of each of the 5 diodes and then calculations of the average failure current \bar{I}_{fail} for each lot (also assume that the standard deviation s of each sampled lot lies within $\pm 0.1\bar{I}_{fail}$).

Table A-1. A Hypothetical EMP Component Database Listing Operating Parameters and Average Failure Currents for Five Different Diodes

Diode # n	$A_{p-n}(\text{cm})^2$	V_{p-n} (V)	I_{sat} (A)	V_{FB} (V)	\bar{I}_{fail} (A)
1	0.20	1.0	-1.5E-14	-9.5	-1.2E-3
2	0.25	1.5	-1.9E-14	-13.0	-3.0E-3
3	0.19	0.7	-8.0E-15	-8.0	-9.7E-4
4	0.30	2.1	-2.2E-14	-11.2	-4.5E-3
5	0.22	1.3	-1.0E-14	-10.0	-1.6E-3

Now, during a system analysis, the component resolution is focused down to the electronic piece-part level, and another diode, which will be called diode #6 (not in the database) is under analysis. The provided operating parameters for diode #6 are contained in the data sequence <0.27, 1.6, -1.7E-14, -11.9> (which is called a *tuple*), and correspond to A_{p-n} , V_{p-n} , I_{sat} , and V_{FB} , respectively. Question: can the provided database on five experimentally failed diodes provide guidance to an estimation of the most likely failure current level for diode #6?

To address this question, certain basic concepts of fuzzy set theory are applied to the database. First, an important distinction must be made: the parameter data in the database are *crisp* numbers; that is, each parameter value is represented by a real number that is exactly known to a specified number of decimal points. There is, however, a *fuzzy* relation that correlates each particular operating parameter (or *attribute*)

of diode #6 to the same parameter for diodes #1 through #5. This fuzzy relation S is defined for an ordered pair of crisp real numbers $\{(x,y) | x \in X, y \in Y\}$ and is characterized by a *similarity relation* $\mu_S(x,y)$, where μ_S gives the degree to which x is similar to y . In this case, the crisp data sets X and Y are defined as $X = X_n \equiv \{\text{attributes of diode } \#n\}$ and $Y = Y_m \equiv \{\text{attributes of diode } \#m\}$, where $n,m = 1,2,3,4,5,6$. The similarity relation $\mu_S(x,y)$ is uniquely defined for each domain of permissible values of a particular diode attribute; the range is $0 \leq \mu_S \leq 1$.

Determining $\mu_S(x,y)$ for a particular attribute domain requires three steps. First, all permissible database values of the attribute are listed. For example, for the diode attribute A_{p-n} , Table A-1 is queried and the value domain $\{0.20, 0.25, 0.19, 0.30, 0.22\}$ is determined, corresponding to diodes #1 through #5, respectively. Second, the value of the same attribute for the CUA (diode #6) is added to the existing attribute domain, and the maximum and minimum values within the domain are determined. Again, for the attribute A_{p-n} , the value corresponding to diode #6 (0.27) is added to the domain, and the resulting maximum (0.30) and minimum (0.19) values are determined. Finally, for $x,y \in \{\text{attribute domain}\}$,

$$\mu_S(x,y) = 1 - \frac{|x-y|}{v_{\max} - v_{\min}} \quad (\text{A-1})$$

where $v_{\max} \equiv$ maximum domain value and $v_{\min} \equiv$ minimum domain value. For A_{p-n} , the similarity relation is $\mu_S(x,y) = 1 - |x-y|/0.11$. This relation holds for all x and y within the attribute domain. Table A-2 shows this similarity relation in tabular form. Note that similarity values, or *grades*, between intra-database elements are given, as well as grades between database and external data.

The similarity relation $\mu_S(x,y)$ is next determined over the domains of the attributes V_{p-n} , I_{sat} , and V_{FB} , and the resulting relations are stored in tabular form. Finally, a table can be generated by sampling the four similarity relation tables for data relating attributes of diode #6 to corresponding attributes of diodes #1 through #5 (Table A-3). This last table can be generated directly from Equation (A-1) if intra-database values of $\mu_S(x,y)$ are of little or no interest to the analyst. In Table A-3, the columns represent the four attribute types that diode #6 shares with diodes #1 through #5; the rows represent the similarity between each diode in the database and diode #6 as a function of attribute type.

Table A-2. Similarity Relation $\mu_S(x,y)$ Over the Attribute Domain A_{p-n} .

Diode #n	1	2	3	4	5	6
1	1	0.55	0.91	0.09	0.82	0.36
2	0.55	1	0.45	0.55	0.73	0.82
3	0.91	0.45	1	0	0.73	0.27
4	0.09	0.55	0	1	0.27	0.73
5	0.82	0.73	0.73	0.27	1	0.55
6	0.36	0.82	0.2	0.73	0.55	1

Table A-3. Similarity Values Between Diodes #1 Through #5 and Diode #6 for the Attributes A_{p-n} , V_{p-n} , I_{sat} , and V_{FB}

Diode Attribute →	A_{p-n}	V_{p-n}	I_{sat}	V_{FB}
$\mu_S(1,6)$	0.36	0.57	0.86	0.52
$\mu_S(2,6)$	0.82	0.93	0.86	0.78
$\mu_S(3,6)$	0.27	0.36	0.36	0.22
$\mu_S(4,6)$	0.73	0.64	0.64	0.86
$\mu_S(5,6)$	0.55	0.79	0.50	0.62

Now, a query is addressed to Table A-3: What is the overall similarity between diode #6 and each diode in the database, where the logical intersection $\{\mu_S(x,6)$ over the attribute domain A_{p-n} and $\mu_S(x,6)$ over the attribute domain V_{p-n} and $\mu_S(x,6)$ over the attribute domain I_{sat} and $\mu_S(x,6)$ over the attribute domain $V_{FB}\}$ is evaluated to quantify the overall similarity? If a similarity relation $\mu_S^{ATTR(n)}(x,y) = \mu_S(x,y)$ over the attribute domain n is the single element of the fuzzy set $S_{x,y}^{ATTR(n)}$, then the above query can be symbolically expressed as

$$\begin{aligned}
 S_{1-5 \leftrightarrow 6}^{OVERALL} &= \sum_{x=1}^5 \left[\bigcap_{n=1}^4 S_{x,6}^{ATTR(n)} \right] / Diode\#x = \sum_{x=1}^5 \left[\bigwedge_{n=1}^4 \mu_S^{ATTR(n)}(x,6) \right] / Diode\#x \\
 &= [\mu_S^{ATTR(1)}(1,6) \wedge \mu_S^{ATTR(2)}(1,6) \wedge \mu_S^{ATTR(3)}(1,6) \wedge \mu_S^{ATTR(4)}(1,6)] / Diode\#1 + \dots \quad (A-2) \\
 &\quad + [\mu_S^{ATTR(1)}(5,6) \wedge \mu_S^{ATTR(2)}(5,6) \wedge \mu_S^{ATTR(3)}(5,6) \wedge \mu_S^{ATTR(4)}(5,6)] / Diode\#5.
 \end{aligned}$$

where $\bigcap_n \equiv$ intersection summation operator, $\bigwedge_n \equiv$ minimum summation operator, and $x \wedge y \equiv$ the minimum of x and y . The data in Table A-3 are used to evaluate Equation (A-2):

$$\begin{aligned}
 S_{1-5 \leftrightarrow 6}^{OVERALL} &= [0.36 \wedge 0.57 \wedge 0.86 \wedge 0.52]/Diode\#1 \\
 &+ [0.82 \wedge 0.93 \wedge 0.86 \wedge 0.78]/Diode\#2 \\
 &+ [0.27 \wedge 0.36 \wedge 0.36 \wedge 0.22]/Diode\#3 \\
 &+ [0.73 \wedge 0.64 \wedge 0.64 \wedge 0.86]/Diode\#4 \\
 &+ [0.55 \wedge 0.79 \wedge 0.50 \wedge 0.62]/Diode\#5 \\
 &= 0.36/Diode\#1 + 0.78/Diode\#2 + 0.22/Diode\#3 \\
 &+ 0.64/Diode\#4 + 0.50/Diode\#5 .
 \end{aligned}$$

From this evaluation, it is seen that diode #6 is *very* similar to diode #2 and *fairly* similar to diode #4, where *very* and *fairly* are quantifiers bounded by the scope of the database. When this information is combined with the given values of I_{fail} in Table A-1, a good estimate of I_{fail} for diode #6 is determined to be about -3.5 to -4.0 mA.

The evaluation process presented above can easily be automated in the form of a computer program, and can be extended to a component database with thousands of similar item entries, as in SCORCH. However, when the quantity of sampled data grows to a very large amount, simple inspection of similarity relations becomes increasingly inconclusive. Degrees of similarity (i.e., similarity region (Wunsch and Bell 1968) @ $0.95 < \mu_S \leq 1.00$; similarity region (Kleiner et al. 1974) @ $0.90 < \mu_S \leq 0.95$) need to be established, with traditional statistical methods applied to the similarity data to determine the bounds and meaningfulness of the similarity regions. This fuzzy database model can also be extended to other types of databases, with fuzzy (rather than crisp) data in the database itself, such as failure power = 10.0 ± 0.5 W for an electronic LRU or EMP survivability = moderate to high for an entire system.

Finally, as with any other computer model, the practical validity of the fuzzy database must be verified via experimentation. For the case of the fuzzy component database presented here, verification would involve performing failure experiments on about 30 "identical" samples of diode #6, then using this data to calculate \bar{I}_{fail} for the sampled lot. Next, the "crisp" empirical value \bar{I}_{fail} is compared to the estimated value of I_{fail} for diode #6 derived from the fuzzy database and a correlation is established. For a practical model validation, this "crisp" vs. "fuzzy" correlation process should be carried out on 20 to 30 *different* diodes not in the database (i.e., diode #6 through diode #36).

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3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

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